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The Relationships of Thrust and Shear Deformations in the Southern Part of the Polar Urals as Indicated by Petromagnetic Data

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Abstract—Based on the petromagnetic characteristics of rocks that crop out within the Main Ural Fault zone (MUF) and Voykar–Synya ophiolites the multistage pattern of deformation processes in the study areas has been established. An analysis of the anisotropy of magnetic susceptibility of rock minerals detected the orientation, which allows us to reveal magnetic orientations in minerals recorded as a results of thrust (overthrust) and strike-slip deformations at an early stage of the evolution of the Ural orogenic belt. The main axes of the ellipsoid of anisotropy of the magnetic susceptibility (AMS) associated with regional thrusting, namely, the main stage of formation of the structure of the Urals, have rarely been revealed. This is evidence that thrust petrofabrics are almost completely veiled by superimposed shear deformations.

Keywords: magnetic susceptibility anisotropy, Polar Urals, Main Ural Fault, ophiolites, thrust faults, strike-slip faults

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INTRODUCTION

The rocks of the ophiolite association exposed within the southern part of the Polar Urals and its western framework that are attributed to the Main Ural Fault zone (MUF) have been studied by many researchers in terms of petrology. Among the recent works, the following ones should be noted (Savelieva et al., 2008, 2013; Belousov, 2009; Shmelev, 2011; etc.). The results of the structural and petrostructural studies of ophiolites, including compilation of detailed geological maps, have also been examined by many geologists (for example, Goncharenko and Chernyshov, 1980; Shcherbakov, 1988; Savelieva, 1987; *Stroenie*..., 1990; Savelieva et al., 2008; Shmelev, 2011). In this case, the structural features and stages of the evolution of ophiolite complexes in the MUF zone were not studied practically.

Based on the results of the previous study of the mesostructural elements recorded in rocks of the southern part of the Polar Urals, we distinguished eight stages of deformation related to certain stages of the collision process (Sychev and Kulikova, 2012). The purpose of our research is to clarify the succession of the tectonic evolution of rocks and complexes of the MUF zone and its framework on the basis of an original study of the magnetic characteristics of rocks.

The MUF zone (Figure 1, A was studied at several reference sites of the Rai-Iz massif, the Middle Kechpel River (Fig. 1b), the Khord'yus massif (Fig. 1b), the Mokraya Synya River, and the Dzelyayu block (Fig. 1d). In addition, the conjunction zone of ophiolitic and paleoisland-arc complexes (Lagortayu River) was studied (Fig. 1d). The location sites are located along all of the southern part of the Polar Urals.

Geology of the Research Area. The MUF zone, which is situated in the valley of the Nyrdvomenshor stream in the northern and northeastern framework of the Rai-Iz massif (Fig. 1a), is presented by a thick (up to 2 km) zone of polymictic serpentinite melange, consisting of rounded blocks and boulders of serpentinized dunites and harzburgites, metamorphosed in greenstone facies, basalts and their tuffs, dolerites, siliceous rocks, and carbonaceous–siliceous schists. Upstream is a zone (up to 400 m) of amphibole crystalline schists (Fig. 2a). The MUF zone in the Middle Kechpel River valley (Fig. 1b) is represented by dynamometamorphites of the Palnikshor sequence composed of green and glaucophane schists, garnet-glau-

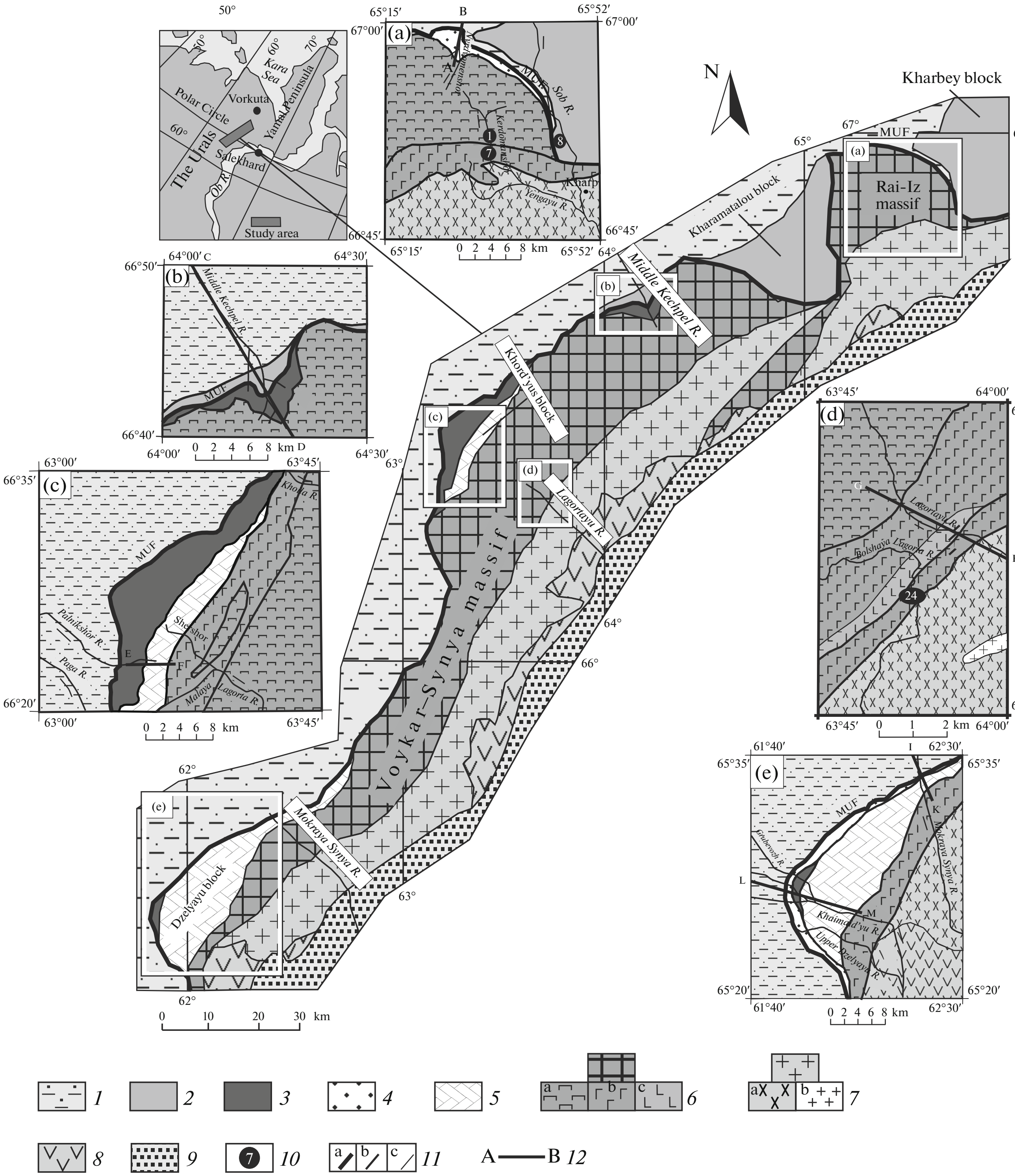

Fig. 1. The tectonic scheme of the southern part of the Polar Urals and study areas. West Uralian megazone: *1*, Paleozoic sedimentary complexes of the shelf and continental slope of the East European Platform, volcanics and Precambrian volcanics of the bimodal series (Lemva allochthon); Central Uralian megazone: *2*, Precambrian metamorphic complexes of the basement of the East European continent (Kharbey and Kharamatalou blocks); Zone MUF (*3–5*): *3*, serpentinite melange; *4*, dynamometamorphites of the Palnikshor sequence; Tagil–Magnitogorsk megazone: *5*, metamorphosed ultramafic and mafic rocks (Dzelyayu complex (V_1?)); *6*, gabbro-ultramafic ophiolite massifs: a, Rai-Iz–Voykar dunite–harzburgite complex of (V_1); b, Kershor dunite-wherlite–clinopyroxenite–gabbro complex (O_3); c, Lagortayu complex of dolerite dikes (O_3–S_1?); *7*, Devonian island-arc granitoids: a, Sob gabbro–diorite–plagiogranite complex (D_1–2); b, Yanoslor granite complex (D_3); *8*, Late Silurian-Devonian island-arc volcanogenic–sedimentary formations; *9*, Mesozoic–Cenozoic cover of the West Siberian plate; *10*, numbers of azimuthal projections of the main axes of the magnetic susceptibility anisotropy ellipsoids (Fig. 4); *11*, faults and geological boundaries: a, Main Ural Fault, b, other faults, c, intrusive contacts; *12*, profiles of geological sections (Fig. 2)

cophane crystalline schists, clinozoisite and garnet amphibolites, crystalline schists of variable composition and blastomilonites (Fig. 2b). The age of the sequence is conditionally attributed to the Late Riphean by analogy with the Ivtyshor Formation. However, this complex of rocks, considered as a sequence, is probably not a stratigraphic subdivision, but a tectonic unit that comprises strata of the bimodal volcanogenic association that experienced intensive dynamometamorphism

The Main Uralian Fault (MUF) in the area of the Khord'yus massif (Fig. 1b) is marked with a zone of glaucophane schists. The Palnikshor sequence has a more complex structure and diverse composition, as well as less-pronounced zoning (Fig. 2b). The Dzelyayu complex is subdivided into the western zone represented by high-strontium gabbro-norites, metagabbroids, and drusites and the eastern zone, which is composed of low-strontium garnet–clinozoisite–amphibole crystalline schists and clinozoisite amphibolites. The age of this complex is defined as early Vendian by Th–U–Pb isotope zircon dating (Remizov and Pease, 2004). In the Mokraya Synya River valley (Fig. 1d) the MUF zone is traced by the outcrops of glaucophane schists and plagiogranites of the Pogurei complex (conditionally, Late Carboniferous–Early Permian) at the western termination of the Dzelyayu complex (Fig. 2d). At the site of the Dzelyayu block (Fig. 1d) the basement of the MUF is presented by a zone of tectonites with a distinct zoning: the western zone with a width of 400–800 m is composed of predominantly green apobasaltic blastomylonites, while the eastern zone (1–2 km) is composed of apobasaltic and apogabbro–amphibolite glaucophanites (Fig. 2e). The Palnikshor sequence at this site is represented by garnet–amphibole–quartz–albite crystalline schists, whereas the Dzelyayu complex is composed of hyperbasites, gabbro-norites, metagabbroids, two-pyroxene granulites, amphibolites, and garnet–clinozoisite–amphibole–plagioclase crystalline schists.

The framework of the MUF zone was studied within the Lemva zone (allochthon). Among the studied rocks are paraschists of the Orang Formation (O_{1-2}), volcanogenic–sedimentary strata of the Molyudshor Formation (O_{2-3}), and flyschoids of the Kechpel Formation (C_3–P_1). Within the Kharbey block, the crystalline schists of the Nyarovei series (RF_2) were studied; within the Kharamatalou block the schists of the Kharamatalou sequence were examined (RF_2). Within the Voykar zone the following complexes were studied: (1) the Rai-Iz–Voykar dunite–harzburgite complex (the U–Pb and Re–Os isotope age data allowed us to reveal Early Vendian magmatic events in the formation of this complex (Savelieva et al., 2006)), (2) the Kershor dunite–wherlite–clinopyroxenite–gabbro complex (the Late Ordovician according to U–Pb isotope zircon data (Remizov et al., 20 10)), (3) the Lagortayu gabbro–dolerite complex of parallel dikes (the U–Pb isotope data are almost exactly consistent with the age of the host gabbroids of the Kershor complex (Remizov et al., 2012), but one can assume a younger Early Silurian age), and (4) the Sob tonalite complex (Early–Middle Devonian according to the Rb–Sr and U–Pb age data (*Geokhimiya*..., 1983; etc.)).

Materials and Methods. In order to study the petromagnetic characteristics of rocks, cubes (~150 pieces, from 1 to 4 depending on the sample size) were cut from oriented samples. The parameters of the magnetic susceptibility anisotropy were measured for each of cubes in the petromagnetic laboratory of Moscow State University using a KLY-4S kappabridge (AGICO Instruments). The measurement results were processed using Anisoft 4.2 software (Chadima and Hrouda, 2006). In order to interpret magnetic orientations azimuthal projections were plotted using Quick-Plot 3.0 software (analyst D.V. Everdingen).

The anisotropy of magnetic susceptibility (AMS) is an informative petromagnetic characteristics of rocks. Among the factors that induced the anisotropy of magnetic susceptibility is crystallization and recrystallization of rocks under uniaxial pressure and high temperature (*Ispolzovanie*..., 1986; Tarling and Hrouda, 1993). The relationship of magnetic anisotropy of rocks with their structural features, in particular, the dependence of AMS on the distribution of the long and short axes of magnetic minerals, allows us to use the AMS measurements for studying the structural elements of deformed rocks (*Ispolzovanie*..., 1986; Tarling and Hrouda, 1993; Borradaile and Henry, 1997; etc.). Numerous studies confirmed the positive correlation link between MSA parameters and deformation of rocks at the qualitative level (Tarling and Hrouda, 1993; Parés and Van der Pluijm, 2004), while the quantitative relationships between them remain controversial (Ježek and Hrouda, 2007; etc.).

Inasmuch as the shape of the MSA ellipsoid is directly dependant on the effective stresses, the coincidence of the orientations of the principal axes of the MSA ellipsoid and ellipsoid deformation is the most important issue (*Ispolzovanie*..., 1986; Borradaile and Henry, 1997). This allows us to interpret the kinematics of faults and to establish the succession of deformation stages using the Anderson criterion (Anderson, 1951).

The AMS is determined by a symmetric tensor of the second rank. The three principal axes of the AMS ellipsoid are denoted as follows: K_1, maximum; K_2, intermediate; and K_3, the minimum magnetic susceptibility. In order to characterize the AMS we have used the following parameters: (1) the average value of the magnetic susceptibility Km (1E-06 SI); (2) the magnetic linearity (L); (3) magnetic banding (F); (4) AMS degree (intensity) (Pj); (5) shape parameter (T), which

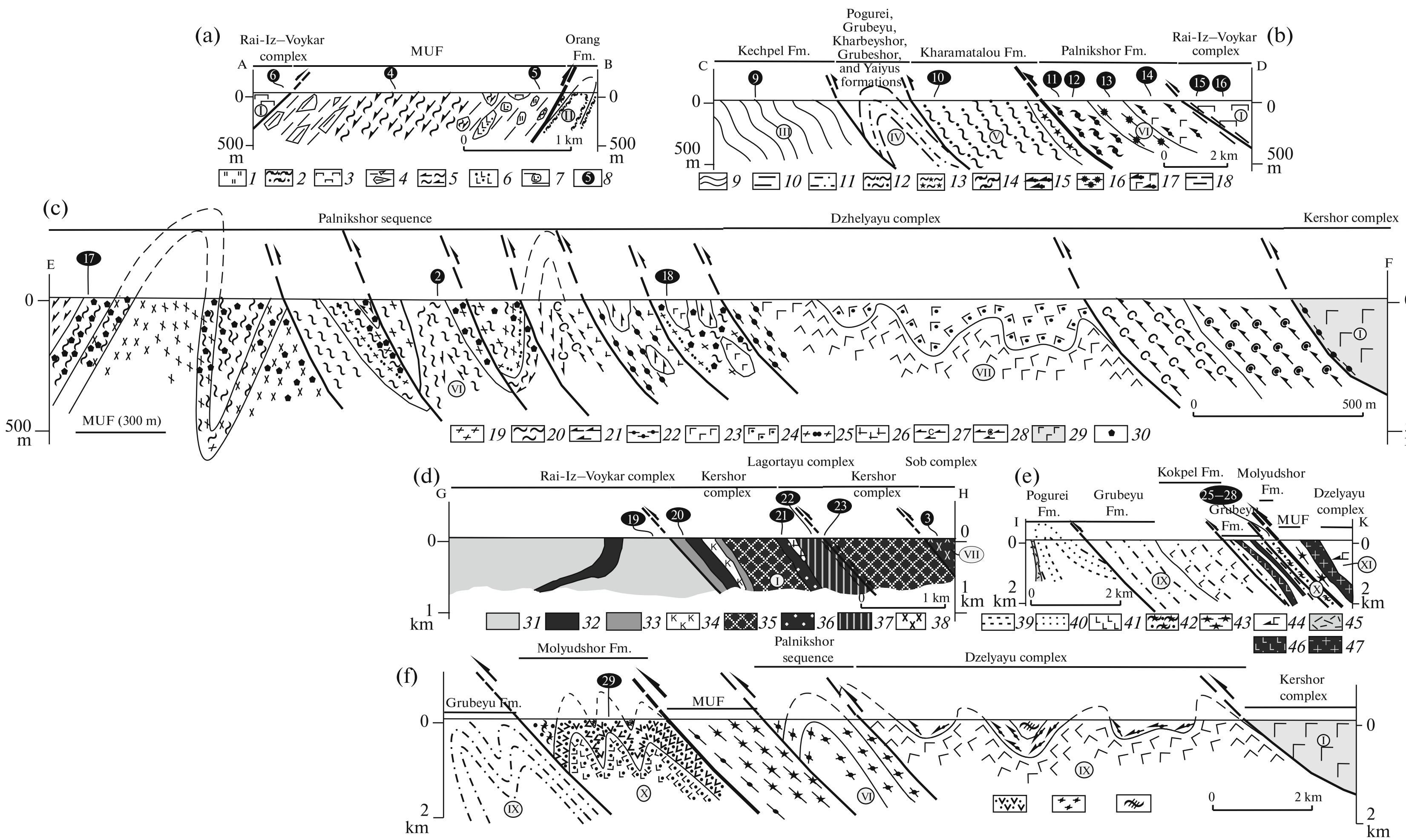

Fig. 2. Geological cross sections across the zone of the Main Ural Fault (their positions are shown in Fig. 1): *1*, phtanites; *2*, sericite–albite–quartz–chlorite schists; *3*, ultramafic rocks; *4*, brecciated and schistose serpentinites; *5*, amphibole crystalline schists; *6*, dolerites, basalts, and their tuffs; *7*, serpentinite melange; *8*, sampling sites of samples for the analysis of the magnetic susceptibility anisotropy and their numbers (azimuthal projections are shown in Fig. 4); *9*, flysch; *10*, mudstones; *11*, siltstones; *12*, green and carbonaceous schists with interbeds of amphibolites; *13*, epidote–glaucophane schists; *14*, garnet–glaucophane crystalline schists; *15*, garnet amphibolites; *16*, glaucophane blastomylonites; *17*, clinozoisite amphibolites with lenses of metagabbroids; *18*, milonites; *19*, amphibole–epidote–quartz–albite crystalline schists; *20*, albite–chlorite–actinolite schists; *21*, amphibolites; *22*, blastomylonites; *23*, gabbro-norites; *24*, metagabbroids and drusites; *25*, metasandstones; *26*, plagiogranites; *27*, clinozoisite amphibolites; *28*, garnet–clinozoisite–amphibole crystalline schists; *29*, amphibolized dunites, wherlites, clinopyroxenites, and gabbros; *30*, garnet; *31*, harzburgites; *32*, dunites; *33*, dunites and wherlites; *34*, clinopyroxenites; *35*, gabbro-norites, pyroxene and hornblende gabbro; *36*, isotropic gabbro; *37*, parallel dikes of dolerites; *38*, diorites; *39*, gravellites; *40*, sandstones; *41*, basalts; *42*, plagioclase–quartz–chlorite schists; *43*, glaucophane schists; *44*, metagabbroids and garnet amphibolites; *45*, rhyolites of the Pozhemayu complex ($Є_3$–O_1); *46*, dolerites of the Orang'yugan–Lemva complex (O_{1-2}); *47*, plagiogranites of the Pogurei complex; *48*, averaged-sized tuffs; *49*, garnet–amphibole–quartz–albite crystalline schists; *50*, two-pyroxene granulites. The Roman numerals in the circles denote: I, Pai-Er plate; II, Orang cover (allochthon); III, Western cover; IV, Upper Kharota and Grubeshor plate; V, Kharamatalou plate; VI, Palnikshor plate; VII, Khordyus plate; VIII, Lagorta plate; IX, Privodorazdelny cover; X, Igyadei–Yegan plate; XI, Dzhelyayu plate.

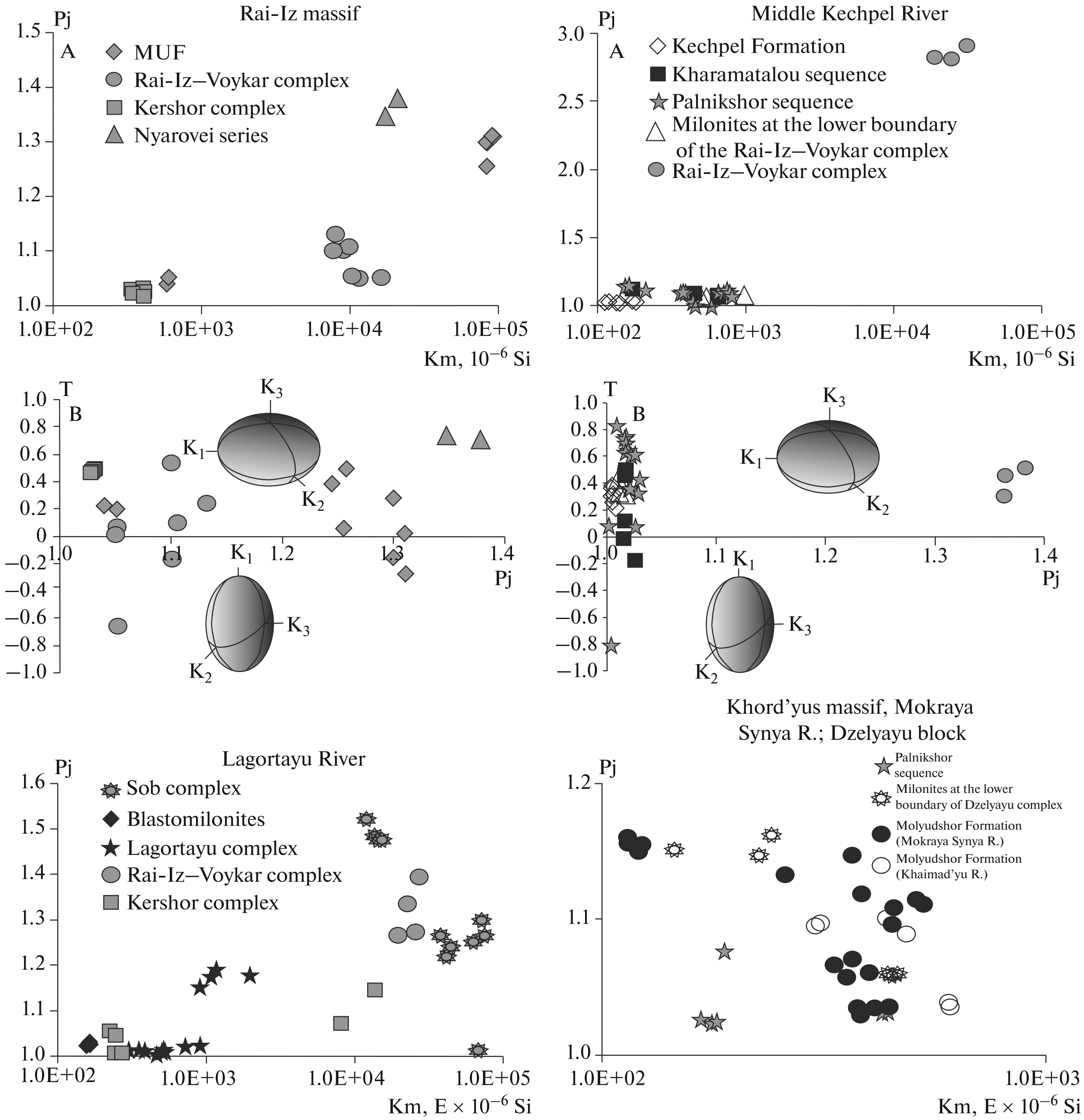

Fig. 3. The distribution plots of the anisotropy of the magnetic susceptibility (AMS) and the mean value of the magnetic susceptibility. AMS ellipsoids show variations in shape and intensity. In the area of the Rai-Iz massif, the orientation of the anisotropy ellipsoid for the MUF zone is associated with fault strains (Fig. 4a, *4*, *5*). The location of the anisotropy ellipsoid for the rocks of the Rai-Iz–Voykar complex in the northern framework of the Rai-Iz massif indicates shear kinematics (Fig. 4a, *6*); in the southern termination of the massif—overthrust kinematics (Fig. 4a, *1*). In the Kershor complex and the Nyarovei series, the compression axes are submeridional and the elongation axes are sublatitudinal and plunging at small angles (Fig. 4a, *7*, *8*), which is associated with shear deformations.

varies from –1 (elongated ellipsoid) to +1 (flattened ellipsoid).

Research Results and their Discussion. The rocks under consideration are subdivided into groups by the average value of volume magnetic susceptibility (VMS). Among them are amphibole crystalline schists of the MUF zone (area of the Rai-Iz massif), the rocks of the Nyarovei series, and the Rai-Iz–Voykar, Sob and partly, the Kershor complexes (the VMS magnitude varies from 10480 up to 105790) (Fig. 3).

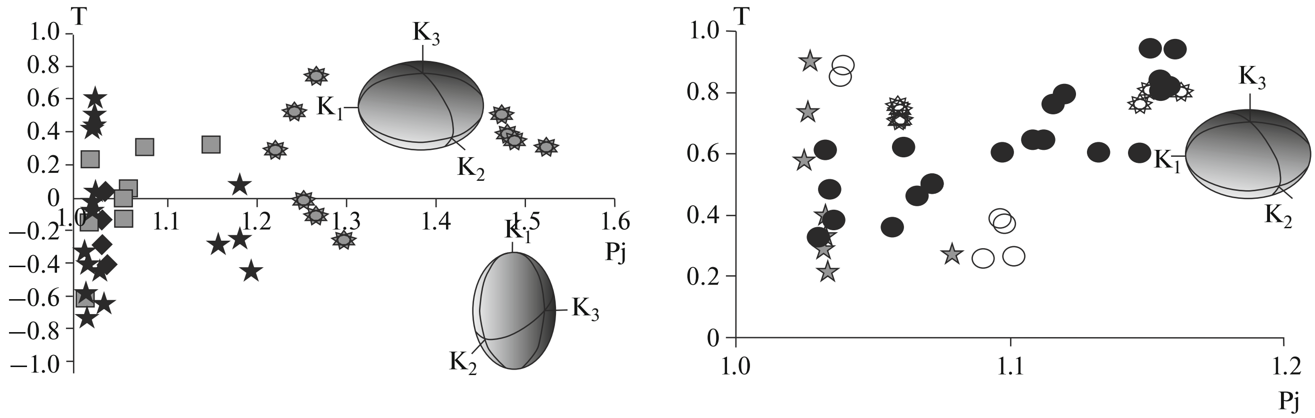

Fig. 3. (Contd.).

In the rest of the studied subdivisions the VMS varies from 99 to 991. Based on the AMS intensity (from 1.2 to 2.9), the same group of rocks is distinguished. The AMS intensity in other geological units varies from 1 to 1.2. The shape of the AMS ellipsoid is extremely flattened.

The orientation of the anisotropy ellipsoid in rocks of the Lemva allochthon and Kharamatalou plate in the Middle Kechpel River basin is determined by fault displacements (Fig. 4a, *9*, *10*). The AMS ellipsoids for rocks of the Palnikshor plate are arranged in a disorderly manner, but they record both normal and strike-slip faults (Fig. 4a, *11–14*). This can be explained by the complex cover–shear structure and the diverse material composition of the rocks. The orientation of the AMS ellipsoid in milonites records the shear component (Fig. 4, *15*). The subvertical orientation of the minimum axis in rocks of the Voykar allochthon is associated with fault deformations (Fig. 4b, *16*). Thus, the orientation of the main axes of MSA ellipsoids for rocks of the Lemva allochthon, Kharamatalou sheet, Palnikshor sheet (close to the MUF zone), and Voykar allochthon is determined by the faulting; the rest of the Palnikshor rocks and milonites are determined by shear deformations.

In the area of the Khord'yus massif, orientations of AMS ellipsoids in rocks of the frontal part of the Palnikshor sequence are related to faulting (Fig. 4b, *17*), whereas in the rear part, they are related to overthrusting (Fig. 4a, *2*). In milonites at the bottom of the Khord'yus plate the orientation of ellipsoids is related to shear displacements (Fig. 4b, *18*).

The orientation of the axes of the AMS ellipsoid in the hyperbasite complex in the Lagortayu River basin is related to shearing (Fig. 4b, *19*). The spatial arrangement of the orientation of the principal axes of the AMS ellipsoids in rock samples from the complex of parallel dikes does not allow us to distinguish a preferred orientation, as was shown in (Kurenkov et al., 2002), due to the development of both shear and fault deformations (Fig. 4b, *21*, *22*). The orientation of the ellipsoid axes in rocks of the Kershor complex was induced by fault deformations (Fig. 4b, *20*, *24*). The orientation of the ellipsoid axes in the zone of blastomylonitization, separated the Kershor and Lagortayu complexes, is related to the shear deformations (Fig. 4b, *23*). The orientation of the ellipsoid axes of the diorites of the Sob complex is related to regional thrusting, subsequent turning, and flattening (Sample 8809) of the dip and strike of a geological body (Fig. 4b, *3*) towards the frontal part of the thrust and separated ophiolitic and paleoisland-arc complexes.

Fault displacements are mainly recorded in the rocks of the Molyudshor Formation (Mokraya Synya River basin and the Dzelyayu block (Fig. 4b, *25–29*).

All the above-described orientations of the AMS ellipsoids are correlated with the stages of deformation processes. Only a few orientations associated with the thrusting (overthrusting) were identified. This is evidence that thrust petrofabrics are almost completely veiled by subsequent shear deformations. The situation is more complicated with deformations that we interpret as shear ones, according to the analysis of mesostructural data. The displacements within the MUF occurred not only along one or a few planes, but within the fault zone as a whole, whose width reaches 15–20 km in some "swells." The splitting of this zone can result in the formation of extension and compression zones. A combination of horizontal extension and a strike-slip (transtension) was revealed for these stages. Consequently, at the later stage of the early collision stage, displacements along oblique slip faults occurred. In our view, the chaotic orientation of the AMS ellipsoid axes is associated with the shearing stage, when petrophysical parameters that are characteristic of the thrusting stage were most likely changed.

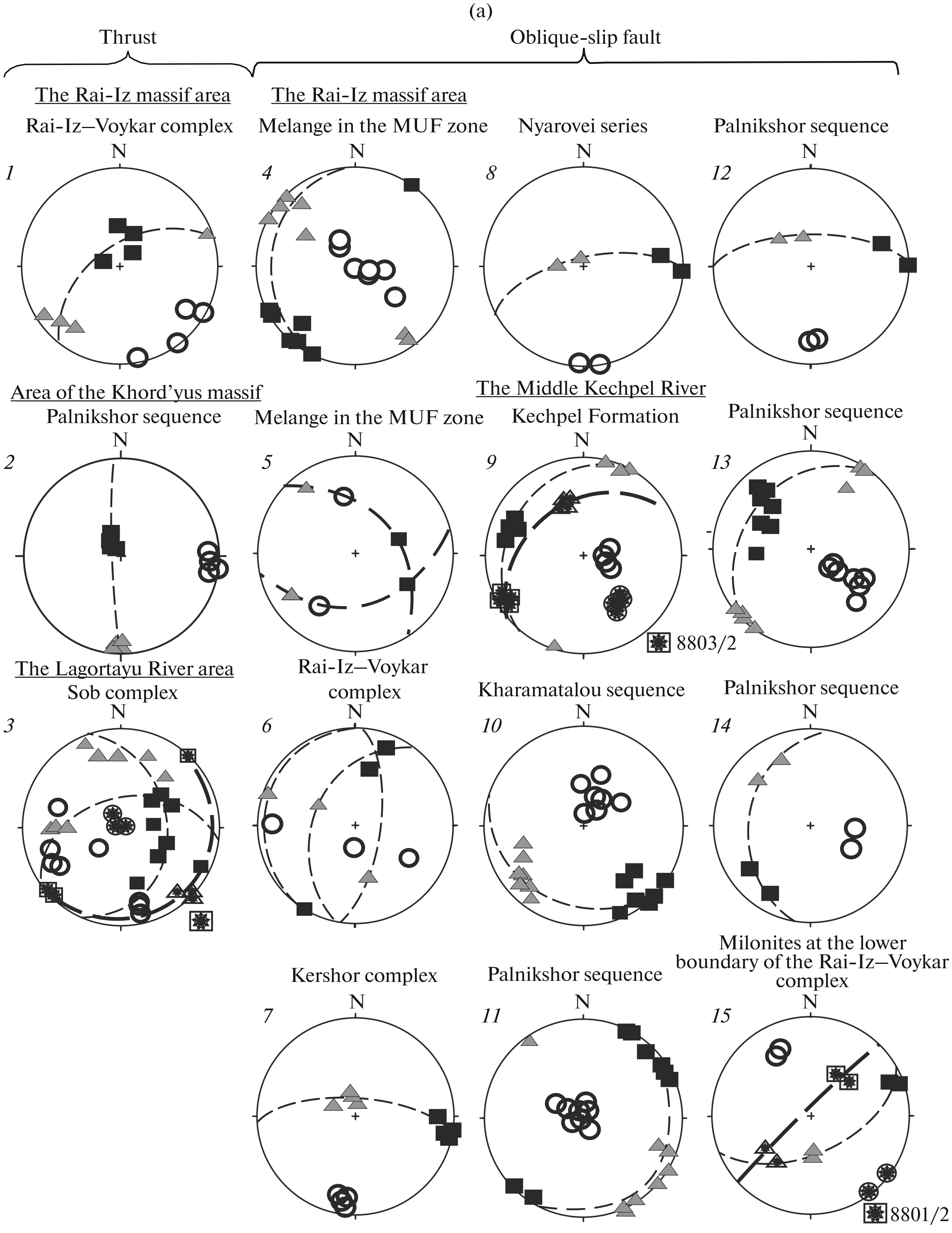

Fig. 4. Azimuthal projections of orientations of the AMS ellipsoid principal axes (Schmidt net, lower hemisphere) (a, b). The arcs of the large circle show orientations of the magnetic banding. The main axes are oriented according to the geographic coordinate system.

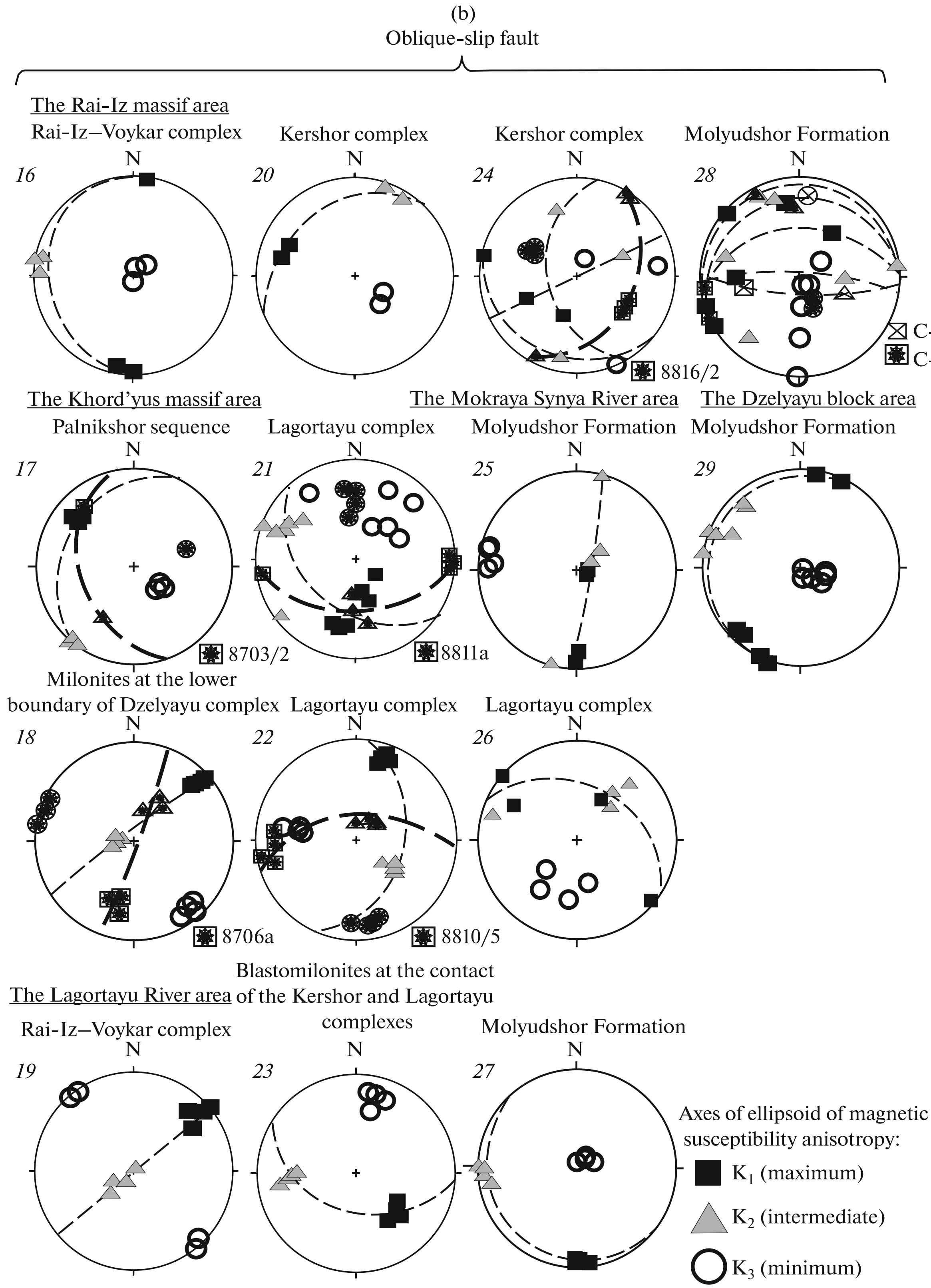
(b)
Oblique-slip fault
The Rai-Iz massif area
Rai-Iz–Voykar complex
Kershor complex
Kershor complex
Molyudshor Formation
N
16
20
24
28
8816/2
C-5
C-9
The Khord'yus massif area
The Mokraya Synya River area
The Dzelyayu block area
Palnikshor sequence
Lagortayu complex
Molyudshor Formation
Molyudshor Formation
17
21
25
29
8703/2
8811a
Milonites at the lower boundary of Dzelyayu complex
Lagortayu complex
Lagortayu complex
18
22
26
8706a
8810/5
The Lagortayu River area
Blastomilonites at the contact of the Kershor and Lagortayu complexes
Rai-Iz–Voykar complex
Molyudshor Formation
19
23
27
Axes of ellipsoid of magnetic susceptibility anisotropy:
K_1 (maximum)
K_2 (intermediate)
K_3 (minimum)

Fig. 4. (Contd.).

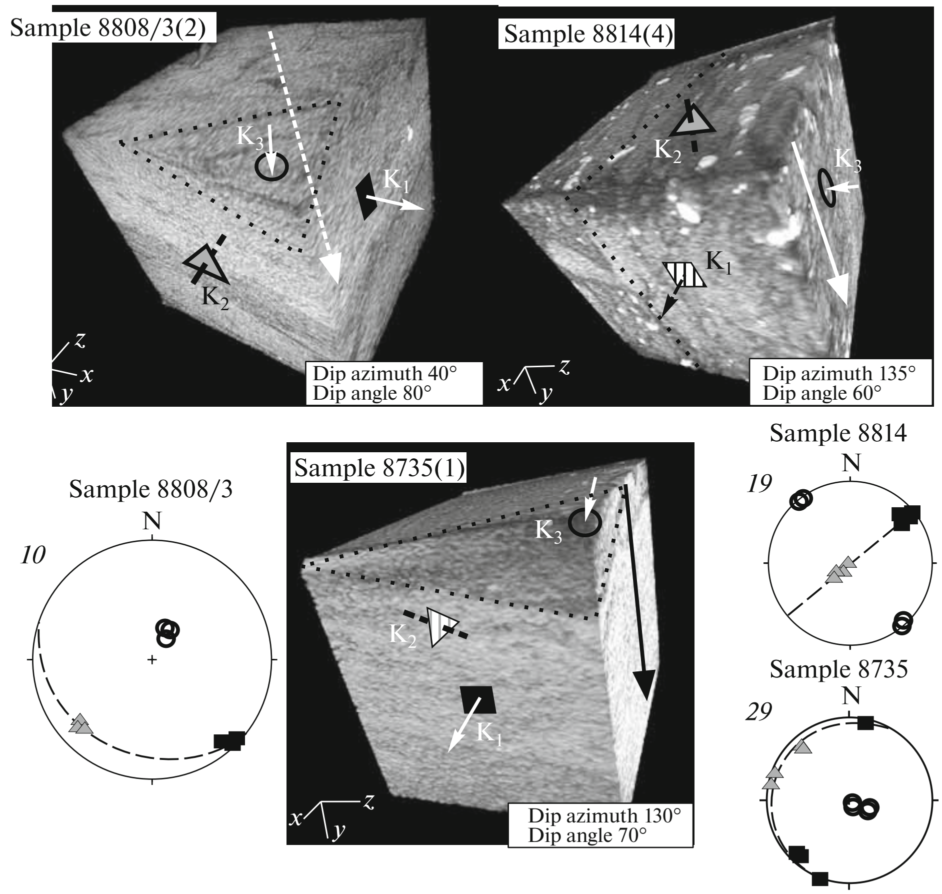

Fig. 5. The relationships of planar elements in rock samples that were used to measure AMS. The principal AMS ellipsoid axes: K_1, minimum, K_2, intermediate, K_3, maximum. The direction of dipping of the sample oriented at the sampling is shown by long arrow. In the right lower corner, the dip and strike of a sample; the dotted line is the orientation of planar elements in a rock sample. The cubes are oriented according to the geographical system of coordinates. The figure in brackets after the number of a sample is the number of the cube cut from the given sample. Sample 8808/3, amphibole–albite–quartz schist (Kharamatalou sequence); Sample 8814, harzburgite (Rai-Iz–Voykar complex); Sample 8735, plagioclase–quartz–chlorite schist Molyudshor Formation). The X-Ray computed tomographic analysis was performed at the Geomodel resource center (SPbSU), analyst M.V. Nikitina.

CONCLUSIONS

We obtained the most complete and comprehensive pattern via an analysis of the anisotropy of magnetic susceptibility, which confirms the development of the shear process within milonitization zones that separate the tectonic units, as well as in the distribution zones of porphyroblast textures. In order to analyze the magnetic susceptibility anisotropy, orientations of planar elements in rock samples, arranged according to the directions of the main axes of the AMS ellipsoid (the minimum axis is perpendicular to the planar elements; the maximum and intermediate axes are parallel to the planar elements) (Fig. 5), which confirms the statement about the relationship between the rock textures and the AMS ellipsoid principal axes.

At this stage of research, unfortunately, we are not able to evaluate the quantitative relationships between different parameters of the MSA and finite deformation, since it is hardly possible to carry out a strain analysis of the rocks of the studied area due to a lack of strain indicators.

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